

# Nubia–Arabia–Eurasia plate motions and the dynamics of Mediterranean and Middle East tectonics

Robert Reilinger<sup>1</sup> and Simon McClusky<sup>2</sup>

<sup>1</sup>Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139, USA.

E-mail: reilinge@erl.mit.edu

<sup>2</sup>Research School of Earth Sciences, Australian National University, Canberra, ABN: 52-234-063-906, Australia

Accepted 2011 June 28. Received 2011 June 9; in original form 2011 March 10

## SUMMARY

We use geodetic and plate tectonic observations to constrain the tectonic evolution of the Nubia–Arabia–Eurasia plate system. Two phases of slowing of Nubia–Eurasia convergence, each of which resulted in an  $\sim 50$  per cent decrease in the rate of convergence, coincided with the initiation of Nubia–Arabia continental rifting along the Red Sea and Somalia–Arabia rifting along the Gulf of Aden at  $24 \pm 4$  Ma, and the initiation of oceanic rifting along the full extent of the Gulf of Aden at  $11 \pm 2$  Ma. In addition, both the northern and southern Red Sea (Nubia–Arabia plate boundary) underwent changes in the configuration of extension at  $11 \pm 2$  Ma, including the transfer of extension from the Suez Rift to the Gulf of Aqaba/Dead Sea fault system in the north, and from the central Red Sea Basin (Bab al Mandab) to the Afar volcanic zone in the south. While Nubia–Eurasia convergence slowed, the rate of Arabia–Eurasia convergence remained constant within the resolution of our observations, and is indistinguishable from the present-day global positioning system rate. The timing of the initial slowing of Nubia–Eurasia convergence ( $24 \pm 4$  Ma) corresponds to the initiation of extensional tectonics in the Mediterranean Basin, and the second phase of slowing to changes in the character of Mediterranean extension reported at  $\sim 11$  Ma. These observations are consistent with the hypothesis that changes in Nubia–Eurasia convergence, and associated Nubia–Arabia divergence, are the fundamental cause of both Mediterranean and Middle East post-Late Oligocene tectonics. We speculate about the implications of these kinematic relationships for the dynamics of Nubia–Arabia–Eurasia plate interactions, and favour the interpretation that slowing of Nubia–Eurasia convergence, and the resulting tectonic changes in the Mediterranean Basin and Middle East, resulted from a decrease in slab pull from the Arabia-subducted lithosphere across the Nubia–Arabia, evolving plate boundary.

**Key words:** Space geodetic surveys; Plate motions; Continental neotectonics; Dynamics of lithosphere and mantle; Kinematics of crust and mantle deformation.

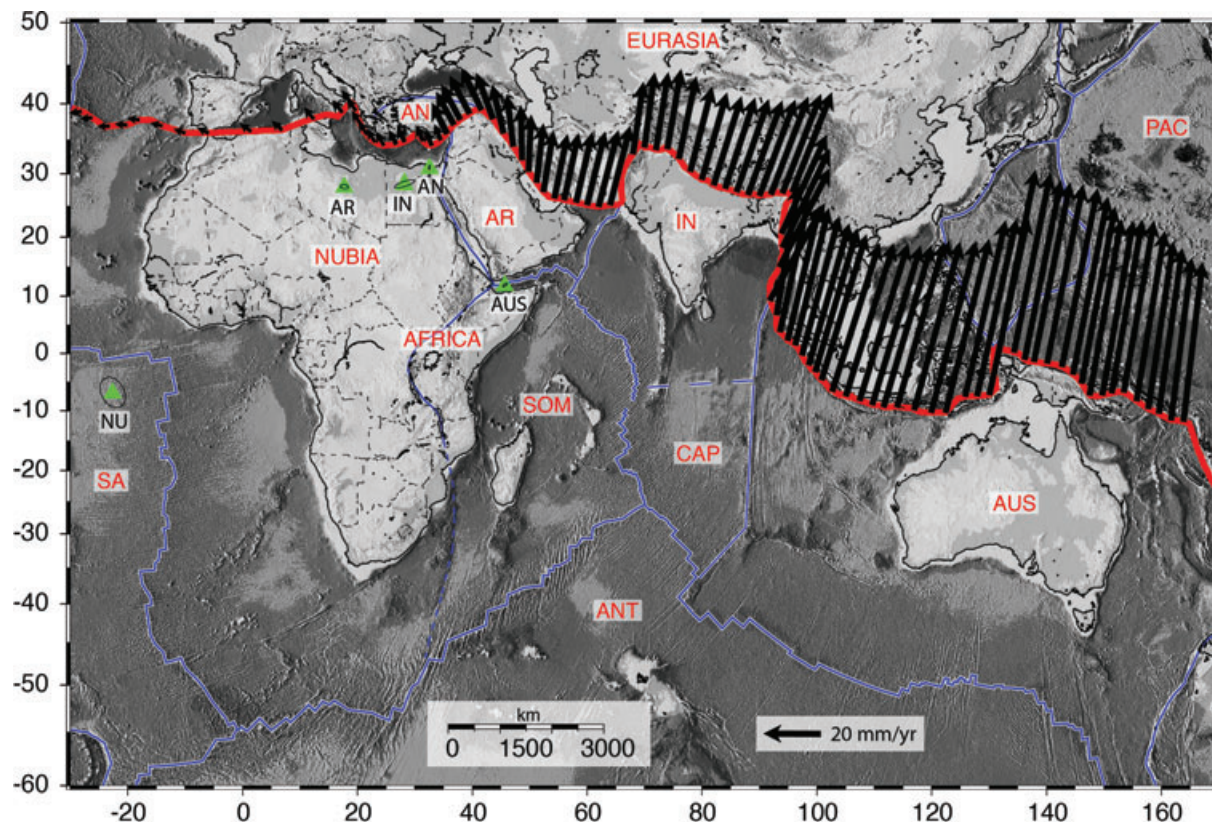
## INTRODUCTION

The southern boundary of the Eurasian tectonic plate is characterized by a broad, complex zone of convergence, extending for  $> 15\,000$  km ( $> 1/3$  of the circumference of the Earth) from Gibraltar to westernmost China (Fig. 1). The wide boundary zone accommodates the northward motion of the Nubia, Arabia, Indian/Capricorn and Australian plates since  $> 150$  Ma, via northward subduction of the Neotethys oceanic lithosphere (e.g. Dercourt *et al.* 1979). This region is among the most seismically active on the Earth, the hazards from which are exacerbated by much of the boundary being subject to great earthquakes, with many occurring at shallow depths within the interior of the Eurasian land mass (e.g. Bilham 2006).

The nature of the forces driving/resisting the motion of the Earth's tectonic plates remains one of the most fundamental questions in global tectonics (e.g. Elsasser 1971; Forsyth & Uyeda 1975; Hager

& O'Connell 1981; Wortel & Spakman 2000; Conrad & Lithgow-Bertelloni 2002; Le Pichon & Kreemer 2010). During the past  $\sim 25$  yr, our ability to measure motions of the Earth's surface to accuracies of  $< 1$  mm yr<sup>-1</sup> on a global scale with the global positioning system (GPS; e.g. Hager *et al.* 1991), and continuing improvements in plate tectonic reconstructions (e.g. McQuarrie *et al.* 2003; DeMets *et al.* 2005; Molnar & Stock 2009), are providing new constraints on plate kinematics. Quantification of plate motions and, most importantly, changes in plate motions allow investigation of how changes in motion may be related to tectonic 'events' along plate boundaries. Since the Earth's plates have very little kinetic energy, motion changes reflect directly the change in the balance of forces driving plate motions (e.g. Molnar & Stock 2009; ArRajehi *et al.* 2010).

There has been a resurgence of interest in the dynamics of Africa–Arabia–Eurasia plate interactions during the past few years



**Figure 1.** Rates of convergence with respect to Eurasia for the Nubian (NU), Arabian (AR), Indian/Capricorn (IN/CAP) and Australian (AUS) plates (note that the AUS plate east of 130°E converges with the W Pacific plate system). Triangles show the locations of Euler poles with respect to Eurasia for each plate (tabulated in Table S2). Blue lines show main plate boundaries, dashed where inferred or distributed. The boundaries of the Capricorn Plate are not well defined and are shown schematically (DeMets *et al.* 2005). Plate name abbreviations: SOM, Somalia; AN, Anatolia; ANT, Antarctica; PAC, Pacific; SA, South America.

as a result of new constraints on crust/mantle structure and deformation from seismic studies (tomographic structure and anisotropy), the determination of global-scale, precise geodetic estimates of plate motions and deformations and improved resolution of plate tectonic reconstructions (see Le Pichon & Kreemer 2010 for a recent review). McKenzie (1970), McKenzie *et al.* (1970), Le Pichon & Angelier (1979) and Le Pichon & Gaulier (1988) placed the tectonic evolution of the Mediterranean and Red Sea into a plate tectonic framework, recognizing the importance of variations in relative plate motions for driving tectonic events along plate margins, including the initiation of Red Sea extension, the Dead Sea Fault and backarc spreading in the Aegean. McClusky *et al.* (2000) used geodetic observations to demonstrate that the rate of westward motion of the Anatolian region increases towards the Hellenic Trench, supporting the dominant role of subduction and trench rollback in driving E. Mediterranean tectonics (Royden 1993). Jolivet & Faccenna (2000) recognized the simultaneity of the onset of extension in the Mediterranean and suggested that extension resulted from the initiation of Nubia/Arabia–Eurasia continental collision that caused slowing of Nubia absolute plate motion (i.e. motion with respect to the mantle) and associated backarc extension in the Mediterranean Basins. Wortel & Spakman (2000) and Govers & Wortel (2005) used seismic tomography and other geophysical and geological observations to demonstrate the role of slab detachment and segmentation [subduction transfer edge propagator (STEP) faults] in modifying trench retreat and deformation of the overriding lithosphere. Bellahsen *et al.* (2003) argued on the ba-

sis of analogue experiments that variations in the subduction pull along strike of the Nubia–Arabia/Eurasia subduction boundary, and weakening of the Nubia/Arabia Plate (prior to separation) by the Afar plume provide a plausible explanation for Nubia and Somalia separation from Arabia. Le Pichon & Kreemer (2010) emphasize the role of toroidal asthenospheric flow around the eastern edge of the Nubian oceanic lithosphere subducting along the Hellenic Arc, in addition to slab rollback in driving counter-clockwise rotation of Arabia and Anatolia.

In this paper, we build on these and our earlier studies (ArRajehi *et al.* 2010; McClusky *et al.* 2010) using geodetic and plate tectonic observations to reconstruct the tectonic evolution of the Nubia/Somalia–Arabia plate boundaries since the Late Oligocene/Early Miocene (~25 Ma), when Arabia separated from Nubia and Somalia, and simultaneously, Nubia–Eurasia convergence decreased by ~50 per cent. We show that the Nubia–Arabia boundary underwent another major reorganization at  $11 \pm 2$  Ma, corresponding to the initiation time of full ocean spreading along the Gulf of Aden that completely decoupled Arabia from Somalia. Reorganization included a further ~50 per cent increase in the rate of Nubia–Arabia motion (due to a slowing of the northward motion of Nubia; McQuarrie *et al.* 2003) as well as changes in the geometry of the northern and southern segments of the plate boundary. Following McQuarrie *et al.* (2003) and ArRajehi *et al.* (2010), we relate changes in Nubia Plate motion to the reduction of the northward ‘pull’ on Nubia from subduction along the Arabia–Eurasia segment of the plate boundary. We further suggest that slowing of



Nubia–Eurasia convergence resulted in southward migration of the Mediterranean trench system, initiating extensional tectonics along the entire Mediterranean (Alboran, central Mediterranean, Aegean Basins). Based on the roughly coherent motion of the entire system of plates presently converging with the southern boundary of Eurasia, we hypothesize that pull by the subducting lithosphere beneath Eurasia is the dominant force driving convergence of this plate system.

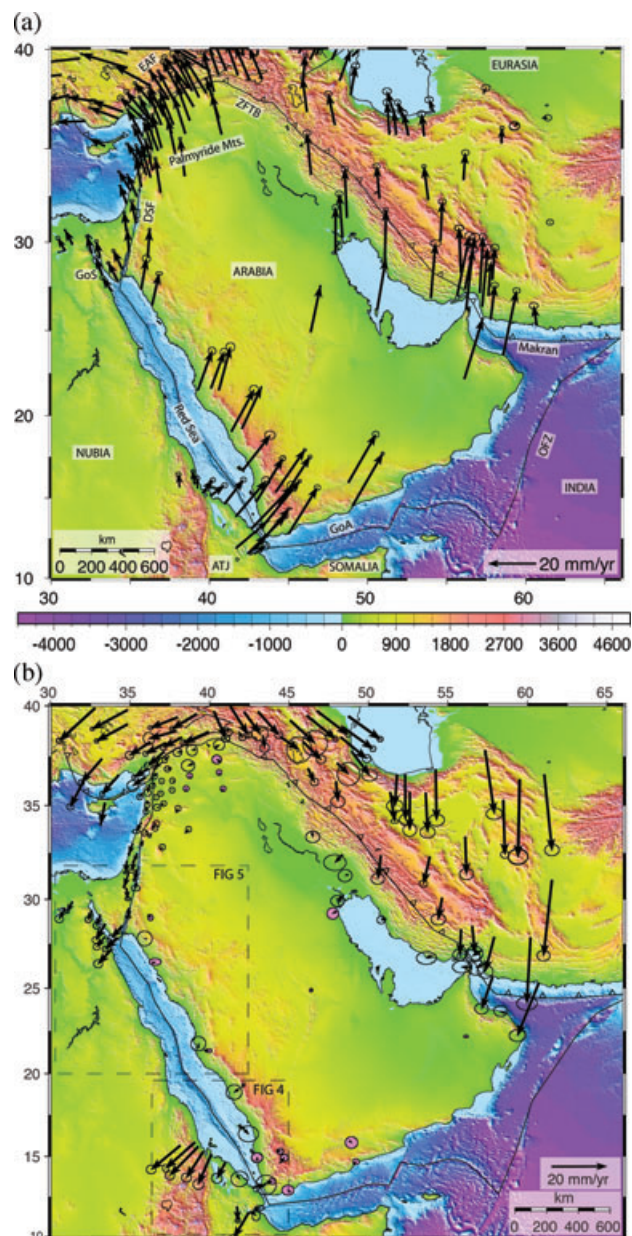
## PRESENT-DAY AND LONG-TERM RELATIVE PLATE MOTIONS

Fig. 2(a) shows velocities and 1-sigma confidence ellipses for GPS sites on Arabia and adjacent plates with respect to a non-rotating Eurasian Plate (also listed in Table S1). The GPS data were processed and uncertainties estimated with the GAMIT/GLOBK software package (Herring *et al.* 2010) using standard techniques described in Reilinger *et al.* (2006). As demonstrated previously, the present-day motion of Arabia and Nubia are well described by an Arabia–Nubia Euler vector ( $31.5 \pm 0.6^\circ\text{N}$ ,  $25.2 \pm 0.7^\circ\text{E}$ ,  $0.393 \pm 0.005^\circ\text{Myr}^{-1}$ ), indicating coherent motion of both plates (see also Fig. 2b for Arabia) at the level of present geodetic observations [i.e.  $\sim 1\text{ mm yr}^{-1}$  or  $<10$  per cent of the rate of Arabia motion with respect to Nubia (McClusky *et al.* 2003; ArRajehi *et al.* 2010)]. The Arabia–Nubia geodetic Euler vector is equal within 1-sigma uncertainties to a plate tectonic Euler vector ( $31.5 \pm 1.2^\circ\text{N}$ ,  $23.0 \pm 2.7^\circ\text{E}$ ,  $0.40 \pm 0.05^\circ\text{Myr}^{-1}$ ) derived from magnetic anomalies in the Red Sea (Chu & Gordon 1998), indicating that Arabia–Nubia motion has not changed significantly in rate or direction since 3 Ma.

McQuarrie *et al.* (2003) used plate circuit closures based on magnetic seafloor anomalies and geological reconstructions of crustal shortening in Iran to estimate the motion of Nubia and Arabia with respect to Eurasia from 59 to 0 Ma. They present their result in terms of the distance a point on the Afro-Arabian plate has moved with respect to Eurasia as a function of time (Fig. 3). Although poorly constrained, McQuarrie *et al.* (2003) find no evidence for significant changes in the orientation of plate convergence (see Fig. 6 and further discussion later). As shown previously by ArRajehi *et al.* (2010), extrapolating the present-day, geodetic motions for Arabia and Nubia with respect to Eurasia back in time indicates that the rate of Nubia–Eurasia convergence has not changed significantly since at least 11 Ma, and Arabia–Eurasia since at least 21 Ma and possibly since the time of separation of Arabia from Africa (Nubia and Somalia) at  $24 \pm 4$  Ma (e.g. Joffe & Garfunkel 1987), an extrapolation of  $>6$  orders of magnitude. Based on these observations, we use precisely determined geodetic motions and plate tectonic reconstructions to constrain the geodynamic evolution of the Nubia–Arabia–Eurasia plate system.

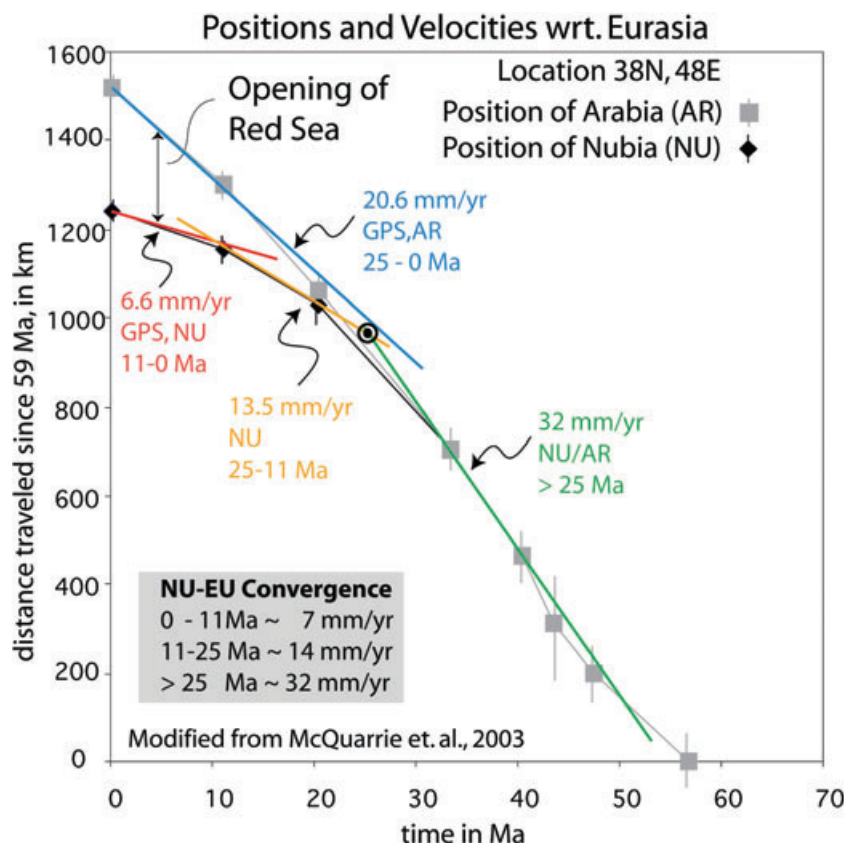
## RECONSTRUCTING NUBIA–ARABIA PLATE MOTION

McClusky *et al.* (2010) have shown from geodetic observations and tectonic structure that a major reorganization of the Nubia–Arabia plate boundary occurred in the southernmost Red Sea at  $9 \pm 4$  Ma, with a preferred timing of  $\sim 13$  Ma based on independent tectonic observations (Le Pichon & Gaulier 1988). Reorganization involved the transfer of rifting from the central Red Sea rift (Bab al Mandab) to the Danakil/Afar Depression and associated counter-clockwise rotation of the intervening Danakil Block with respect to Nubia



**Figure 2.** (a) GPS velocities with respect to Eurasia (spatially decimated for clarity) in and adjacent to the Arabian plate with 1-sigma confidence ellipses. Velocities are tabulated in Table S1. Topography and bathymetry from ([http://topex.ucsd.edu/WWW\\_html/srtm30\\_plus.html](http://topex.ucsd.edu/WWW_html/srtm30_plus.html)). Abbreviations: EAF, East Anatolian fault; GoS, Gulf of Suez; ATJ, Afar Triple Junction; ZFTB, Zagros fold thrust belt; GoA, Gulf of Aden; OFZ, Owens fracture zone. Modified from ArRajehi *et al.* (2010). (b) GPS velocities with respect to Arabia (spatially decimated for clarity) in and adjacent to the Arabian plate with 95 per cent confidence ellipses. Velocity vectors with purple error ellipses were used to estimate the Arabian Plate reference frame. The small residuals indicate that, except for elastic strains near plate boundaries, and possible shortening across the Palmyride fold-thrust belt (Alchalbi *et al.*, 2009), the Arabian plate is not deforming internally at the present level of GPS uncertainties ( $\sim 1\text{ mm yr}^{-1}$ ). Boxes show the locations of Figs 4 and 5. Modified from ArRajehi *et al.* (2010).

about a pole located near  $\sim 17^\circ\text{N}$  latitude. Fig. 4 shows an alternate reconstruction that avoids excessive overlap of unextended terrains in the northern Danakil Depression. This reconstruction involves an initial  $10^\circ$  clockwise, backrotation about the geodetic Euler pole that



**Figure 3.** Motion of a point on the Arabia–Africa plate as a function of time since 59 Ma compared to the geodetic rates extrapolated to this time (modified from McQuarrie *et al.* 2003; ArRajehi *et al.* 2010). Geodetic and plate tectonic rates are equal within uncertainties for Arabia (AR) to >21 Ma and Nubia (NU) to >11 Ma. The convergence rates for NU–EU for different periods are indicated in the inset and illustrated graphically in Fig. 6.

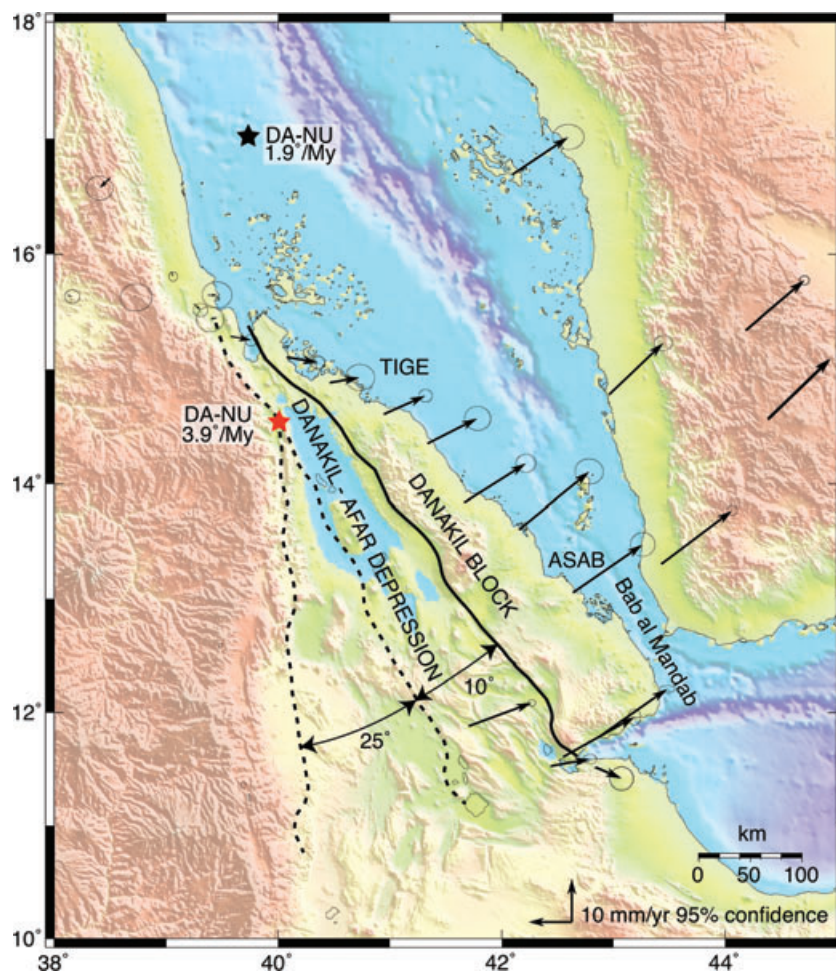
results in contact between unextended terrains in the northernmost Danakil Block and the adjacent Nubia crust at about 5 Ma (i.e.  $10^\circ$  per  $1.9^\circ$  per Myr). We hypothesize that prior to 5 Ma, the Danakil Block–Nubia rotation pole was located near the northern end of the block, south of its present location (Fig. 4). The northward translation of the Euler pole at 5 Ma resulted from the northernmost part of the Danakil Block separating from Nubia at that time. We estimate the pre-5 Ma rotation rate by setting the Danakil Block–Nubia rate to zero at the northern end of the Block (GPS station TIGE), while the rate near the southern end (CGPS station ASAB) continued at the Arabian Plate rate. This backrotation results in closure of the Danakil–Afar Depression without substantial overlap of unextended terrains at  $11 \pm 2$  Ma (i.e.  $5 \text{ Ma} + 25^\circ$  per  $3.9^\circ$  per Myr, and estimating a 15 per cent uncertainty based on rotation rate uncertainties and variations in total closure along strike).

We employ a similar approach to investigate the kinematic evolution of the northernmost Arabia–Nubia boundary. Total post-Late Miocene Fault offset on the southern Dead Sea Fault (SDSF) is estimated to be  $45 \pm 5$  km (e.g. Hempton 1987). The geodetic slip rate along the SDSF is  $4.4 \pm 0.3 \text{ mm yr}^{-1}$  (e.g. Reilinger *et al.* 2006). This indicates that the fault initiated at  $10 \pm 2$  Ma, assuming a constant, average slip rate based on the steady motion of Arabia with respect to Nubia during the past 11 Ma (Fig. 3), and the consistency of geodetic and geomorphic slip rates for the SDSF (Klinger *et al.* 2000; Niemi *et al.* 2001). Similarly, total offset along the northern DSF is estimated to be  $22 \pm 3$  km (Chaimov *et al.* 1990; Gomez *et al.* 2006), with a geodetic slip rate of  $2.4 \pm 0.5 \text{ mm yr}^{-1}$  (Alchalbi *et al.* 2009) indicating an age of initiation of  $9 \pm 3$  Ma.

In Fig. 5, we determine similar, independent estimates of the age of the SDSF from the geodetic strike-slip rate and the structural offset of the southernmost edge of the Sinai Peninsula with respect to the adjacent Arabian Plate ( $11 \pm 2$  Ma), as well as from the width of the Gulf of Aqaba and the geodetic rate of extension [ $11 \pm 3$  Ma; geodetic slip rates from the block model of Reilinger *et al.* (2006)]. We conclude that the most recent phase of activity along the DSF initiated around  $10 \pm 3$  Ma along the full strike of the fault, roughly simultaneously with the change in configuration of the S Red Sea ( $11 \pm 2$  Ma), and about the same time as relative motion between Arabia and Africa increased by  $\sim 50$  per cent (Fig. 3). This conclusion finds further support from estimates of the time required to open the Gulf of Suez, using an 11–25 Ma Arabia–Nubia rate of relative motion that was  $\sim 50$  per cent slower than at present (Fig. 3). As indicated in Fig. 5, the present width would develop in  $13 \pm 6$  Myr, implying initial rifting of Arabia from Africa at about  $24 \pm 6$  Ma, consistent with independent estimates for the initiation of Red Sea rifting (e.g. Garfunkel & Beyth 2006), and demonstrating the internal consistency of this simple reconstruction.

To summarize, geodetic and plate tectonic constraints on the rates of relative plate motion and the structure of the Nubia–Arabia plate boundary (Red Sea) are consistent with the initiation of rifting at  $24 \pm 4$  Ma (Garfunkel & Beyth 2006; ArRajehi *et al.* 2010), and a change to a more N–S orientation in both the northern and southern Red Sea at  $11 \pm 2$  Ma. The apparent simultaneity and similar spatial orientation of these changes suggest they result from changes in Arabia–Nubia plate motions.





**Figure 4.** Backrotation of the western side of the Danakil Block (represented by the solid black line) around the GPS Danakil–Nubia (DA–NU) rotation pole (black star at  $\sim 17^\circ\text{N}$ ) to initial overlap of unextended terrains (at  $\sim 15^\circ\text{N}$ ) after  $10^\circ$  rotation ( $\sim 5$  Ma; easternmost dashed line). A second backrotation around a proposed pole near the location of initial overlap (red star) of an additional  $25^\circ$  (westernmost dashed line) closes the Danakil Depression. Full closure is achieved at  $11 \pm 2$  Ma (see text for discussion).

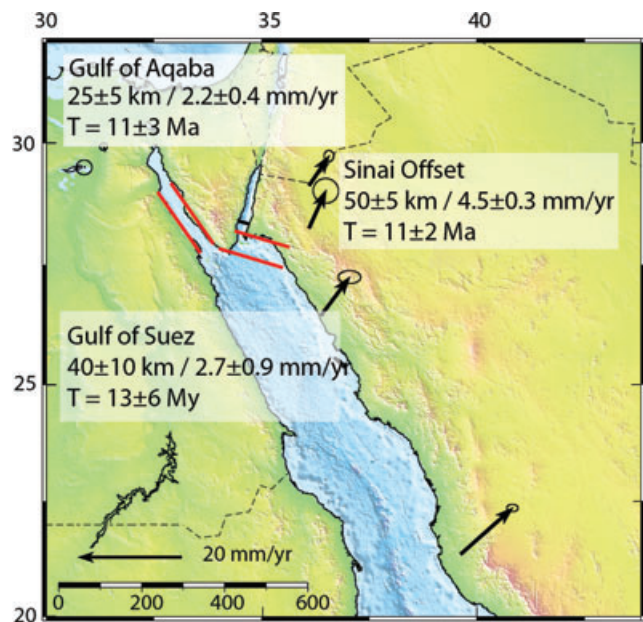
## MEDITERRANEAN EXTENSION AND NUBIA–EURASIA CONVERGENCE

Extension in the Mediterranean Basin (Fig. 6) from the Alboran Sea (Platt & Vissers 1989; Cloetingh *et al.* 1992) across the central Mediterranean (Tyrrenian and Balearic Basins; Dewey *et al.* 1989; Krijgsman & Garces 2004) and the Aegean (Le Pichon & Angelier 1979; Jackson 1994; Gautier *et al.* 1999) initiated roughly simultaneously with the initial slowing of Nubia–Eurasia convergence in the Late Oligocene/Early Miocene ( $\sim 25$  Ma; Jolivet & Faccenna 2000), with a change in the configuration of extension in the Tortonian ( $\sim 11$  Ma). While detailed extension is complex, apparently depending on the configuration and segmentation of the subducted lithospheric plates (Wortel & Spakman 2000; Govers & Wortel 2005), as well as the character of subducted lithosphere (Royden & Husson 2009), the temporal coincidences between extension throughout the Mediterranean Basin and the two-phase slowing of Nubia–Eurasia convergence, the consistency of the southward motion of the trench systems with the directional change in Nubia–Eurasia motion, and theoretical considerations that predict a reduction in the dynamic buoyancy forces acting on the subducted plate as plate convergence slows (Jolivet & Faccenna 2000; Turcotte & Schubert 2002), support the hypothesis that extension in the Mediterranean resulted directly

from changes in Nubia Plate motion, providing a conceptually simple, dynamic cause for Late Oligocene to present-day extensional tectonics within the Mediterranean Basin.

### What caused slowing of Nubia–Eurasia convergence?

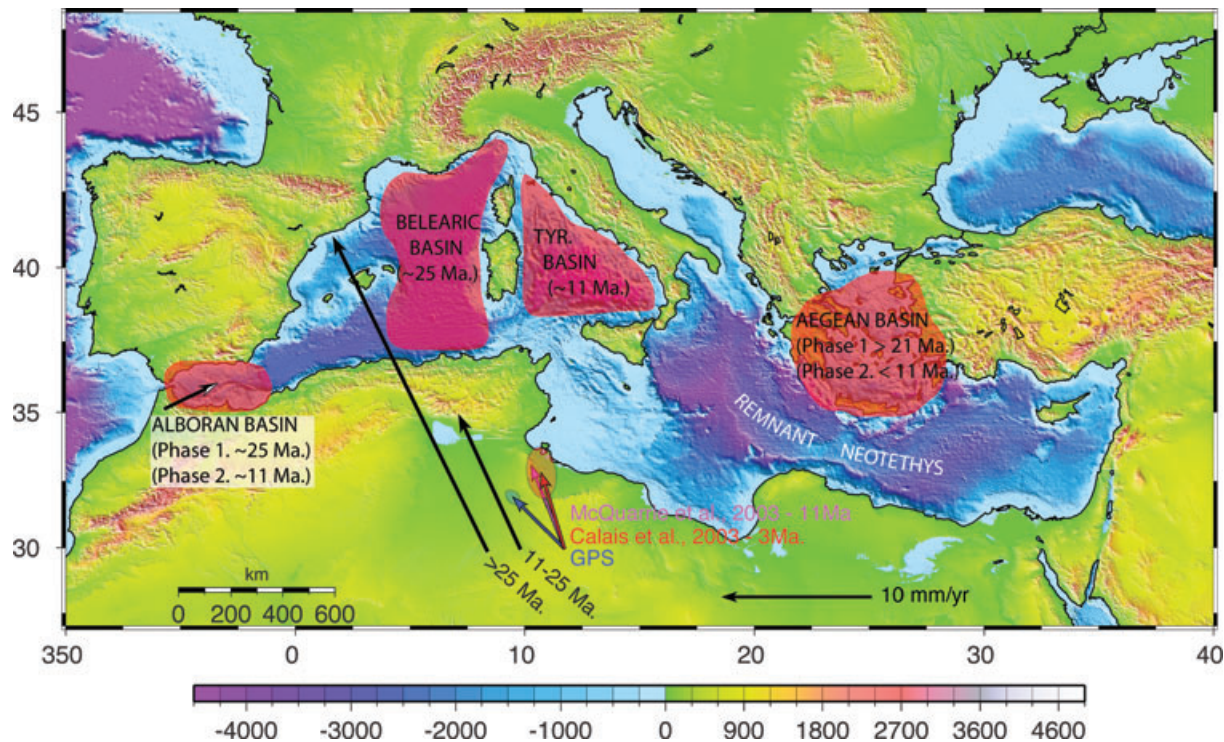
Plate driving forces, deduced primarily on the basis of theoretical considerations (Elsasser 1971; Forsyth & Uyeda 1975; Hager & O'Connell 1981; Conrad & Lithgow-Bertelloni 2002), include (1) pulling of the trailing plate towards the trench due to the sinking of the ocean lithosphere along subduction zones, (2) extension of the overriding plate due to migration of the trench towards the subducting plate (slab rollback), (3) pushing of the plate along mid-ocean ridges due to gravitational sliding of the plate down the oceanic isotherm defining the oceanic lithosphere–asthenosphere boundary, (4) traction forces due to relative motion between the lithosphere and underlying asthenosphere, (5) retarding forces due to continent–continent collision and (6) forces due to friction along strike-slip boundaries (i.e. transform faults). The relative importance of these forces remains the subject of active research (e.g. Billen 2008). Within this context, northward motion and counter-clockwise rotation of the Nubia–Somalia–Arabia plate (prior to



**Figure 5.** Estimates of the age of the Dead Sea fault system from fault slip rates deduced from geodetic measurements [from the block model of Reilinger *et al.* (2006)] and structural offsets. We also show that  $13 \pm 6$  Myr is the estimated time required to open the Gulf of Suez using the pre-11 Ma Arabia–Nubia rate across the Gulf that was  $\sim 30$  per cent of the present geodetic rate (see text for discussion). Velocity vectors show motions with respect to Nubia and their 95 per cent confidence ellipses.

plate separation) with respect to Eurasia was driven in part by subduction of the Neotethys oceanic lithosphere beneath the southern boundary of the Eurasian Plate (e.g. Bellahsen *et al.* 2003; McQuarrie *et al.* 2003).

Rifting along the Red Sea, Gulf of Aden and the East African Rift initiated around  $24 \pm 4$  Ma, apparently following weakening of the Nubia/Somalia/Arabia continental lithosphere by the Afar plume (e.g. Garfunkel & Beyth 2006). At roughly this same time, Nubia–Eurasia convergence slowed and  $\sim$ N–S extension initiated in the Mediterranean. Full ocean spreading (i.e. complete severing of the continental lithosphere and associated extrusion of basaltic magmas) occurred first along the Gulf of Aden (Arabia–Somalia plate boundary), progressing from east to west, between 16 and 11 Ma (Cochran 1981; Ben-Avraham *et al.* 2008), roughly at the same time that Nubia–Eurasia convergence slowed an additional  $\sim 50$  per cent and tectonic changes occurred in the Arabia–Nubia plate boundary and in Mediterranean extension. The temporal coincidence of initial rifting of the Nubia–Somalia–Arabia plate boundaries at  $24 \pm 4$  Ma and initial slowing of Nubia–Eurasia convergence, and the coincidence of the second episode of Nubia–Eurasia slowing with the initiation of ocean spreading in the Gulf of Aden at  $11 \pm 2$  Ma (Le Pichon & Gaulier 1988; ArRajehi *et al.* 2010) are consistent with the notion that incremental severing of the Nubia–Somalia–Arabia plate boundary over time progressively decoupled the African and Arabian plates, thereby reducing the northward pull on Nubia and Somalia from subduction of the Neotethys north of the Arabian segment of the plate boundary (McQuarrie *et al.* 2003). Furthermore, the change to more N–S oriented boundaries along the northern and



**Figure 6.** Bathymetric map showing the ages for the initiation of extension in the Mediterranean and rates of Nubia–Eurasia convergence since 59 Ma. Extension initiated in Late Oligocene/Early Miocene ( $\sim 25$  Ma) coincidental with the initiation of continental rifting along the Red Sea and Gulf of Aden, and a corresponding 50 per cent slowing of Nubia–Eurasia convergence. A second phase of extension in the Tortonian ( $\sim 11$  Ma) coincides with the further 50 per cent slowing of Nubia–Eurasia convergence at that time. Basin extension timing from Cloetingh *et al.* (1992) (Alboran Sea), Dewey *et al.* (1989) and Krijgsman & Garces (2004) (Tyrannian and Belearic seas) and Le Pichon & Angelier (1979), Jackson (1994) and Gautier *et al.* (1999) (Aegean Sea).



southern Red Sea at  $11 \pm 2$  Ma appears consistent with a reduced northward pull on the Nubia and Somalia plates along the roughly E–W oriented Gulf of Aden. This dynamic interpretation is similar to that proposed by Jolivet & Faccenna (2000). They suggest that slowing of Nubia–Eurasia convergence results from the onset of plate collision in the westernmost Mediterranean, which, in turn, reduced compressional stresses in the collision zone and increased the rate of slab rollback. However, the slowing of Nubia–Eurasia convergence in two steps rather than in a more continuous fashion, while Arabia–Eurasia convergence remained approximately constant in spite of  $>10$  Ma of continental collision, seem to support models where slowing of convergence was due to a reduction in the slab pull force (e.g. Hager & O’Connell 1981; Conrad & Lithgow-Bertelloni 2002; McQuarrie *et al.* 2003) rather than the initiation of continental collision.

For more than 100 Ma prior to the initiation of rifting along the Red Sea and Gulf of Aden, Nubia and Arabia convergence with Eurasia was accommodated by subduction of the Neotethys ocean lithosphere beneath Eurasia from the Alboran Sea (westernmost Mediterranean; Fig. 6) to the present-day Makran Trench (Dercourt *et al.* 1979; Fig. 1). The subducting plate was in dynamic equilibrium, maintaining a stable geometry for the downgoing lithosphere. Slowing of Nubia–Eurasia convergence at  $24 \pm 4$  Ma caused an imbalance in the dynamic equilibrium for the subducting plate. All else being equal, slowing of plate convergence at a subduction zone causes a reduction in the dynamic buoyancy forces acting on the subducted plate (Turcotte & Shubert 2002, pp. 242–244), resulting in foundering of the plate and in the case of Nubia–Eurasia convergence, southward migration of the trench system (slab rollback; Royden 1993). This effect was enhanced at  $11 \pm 2$  Ma when Nubia–Eurasia convergence slowed by an additional 50 per cent.

Calais *et al.* (2003) used new magnetic anomalies from the North Atlantic to reexamine motion of the Nubian, Eurasian and North American plates since 3.16 Ma, with Nubia–Eurasia motion being determined indirectly from plate circuit closures. Their comparison with geodetically determined motion between Nubia and Eurasia indicates a marginally significant change in motion since 3.16 Ma, specifically, Nubia–Eurasia convergence has become more oblique with the direction of convergence rotating towards the west by as much as  $30^\circ$  in the central Mediterranean (Fig. 6), while the rate of motion did not change significantly (Calais *et al.* 2003, their fig. 5). These small changes are below the resolution of the plate tectonic reconstruction of McQuarrie *et al.* (2003). To the extent that Neotethys subduction is driving Nubia–Eurasia convergence, as we argue here, this change in direction would imply a decrease in the E component of the slab pull force. The southern Red Sea began full ocean spreading at about 4–6 Ma, although the northern Red Sea continues to be a predominantly continental rift (Cochran 1983; Garfunkel & Beyth 2006). We suggest that the process of severing of the Red Sea Nubia–Arabia plate boundary reduced the force transferred to the Nubia Plate across this boundary that in turn caused a reduction of the eastward component of Nubia–Eurasia motion.

Fig. 1 shows geodetically deduced rates and directions of plate motions for plates converging along the southern edge of Eurasia, including the Nubian, Arabian, Indian/Capricorn and Australian plates. This illustration is schematic in that relative plate motions along at least some segments of the plate boundary, particularly those undergoing continent–continent collision (e.g. Zagros, Tibet) or backarc extension (Mediterranean, Indonesian Arc), are broadly distributed within the overriding Eurasian Plate, and not necessarily

confined to a narrow boundary. Also shown are the locations of the geodetic Euler poles for each plate relative to Eurasia (geodetic Euler vectors are tabulated in Table S2). The relative motions along the boundaries between the plates converging with Eurasia are small in comparison to the rates of convergence [Arabia–India  $\sim 4$  mm yr $^{-1}$  (Reilinger *et al.* 2006; Fournier *et al.* 2008)], India–Australia  $\sim 7$  mm yr $^{-1}$  or  $\sim 10$ –15 per cent of each plates rate with respect to Eurasia). Furthermore, the Euler poles for these plates are located in a relatively small area, indicating coherent rotation of the entire system of plates, at least to first order (Fig. 1). These observations are consistent with the hypothesis that plate convergence along the entire southern boundary of Eurasia is driven predominantly by subduction of the Neotethys oceanic lithosphere.

## CONCLUSIONS

Comparison of geodetic observations with plate tectonic reconstructions for the Arabia–Nubia–Somalia–Eurasia plate system indicates two episodes of slowing of Nubia–Eurasia convergence, the first at  $24 \pm 4$  Ma coinciding with the initiation of Nubia–Arabia rifting along the proto-Afar Triple Junction (then located near the Bab al Mandab) and the second at  $11 \pm 2$  Ma coinciding with the initiation of full ocean spreading in the Gulf of Aden (ArRajehi *et al.* 2010). These relationships support models where slowing of Nubia–Eurasia convergence resulted from a reduction in the north–northeastward pull on Nubia from the Arabian segment of the subducting Neotethys lithosphere that was partially detached from Nubia and Somalia due to the initiation of continental rifting along the Red Sea and Gulf of Aden at  $24 \pm 4$  Ma (McQuarrie *et al.* 2003), and further detached at  $11 \pm 2$  Ma when ocean rifting developed along the Gulf of Aden. The initiation of extensional tectonics in the Mediterranean Basin coincides with the initial slowing of Nubia–Eurasia convergence (Jolivet & Faccenna 2000) and subsequent, intensified extension in the Tortonian ( $\sim 11$  Ma) with the second episode of slowing of Nubia–Eurasia plate convergence at that time. These temporal relationships support the hypothesis that post-Oligocene ( $\sim 30$  Ma) Mediterranean, extensional tectonics were caused by this slowing of Nubia–Eurasia convergence that in turn caused foundering of the subducted plate and associated southward migration of the trench (slab rollback) in the process of reestablishing the dynamic equilibrium of the descending lithosphere. This mechanism provides a simple, unifying, dynamic explanation for the active tectonics of the Mediterranean/Middle East region. The coherent pattern of plate convergence along the southern boundary of Eurasia (Nubian, Arabian, Indian/Capricorn and Australian plates) further suggests that subduction of the Neotethys lithosphere beneath Eurasia is the principal driving force for plate convergence along this entire plate boundary.

## ACKNOWLEDGMENTS

We are very grateful for UNAVCO logistical support and the cooperation of our international partners during the past 23 yr that made this research possible. We thank Philippe Vernant for pointing out the temporal coincidence of Red Sea and Mediterranean extension, and Chuck DeMets, Rob Govers, Duncan Agnew and two anonymous reviewers for their careful and constructive reviews. This research was supported in part by NSF Grants EAR-0305480, EAR-0635702 and EAR-0838488.

## REFERENCES

- Alchalbi, A. *et al.*, 2009. Crustal deformation in northwestern Arabia from GPS measurements in Syria: slow slip along the northern Dead Sea Fault, *Geophys. J. Int.*, **180**, 125–135, doi:10.1111/j.1365-246X.2009.04431.x.
- ArRajehi, A. *et al.*, 2010. Geodetic constraints on present-day motion of the Arabian Plate: implications for Red Sea and Gulf of Aden rifting, *Tectonics*, **29**, TC3011, doi:10.1029/2009TC002482.
- Bellahsen, N., Faccenna, C., Funicello, F., Daniel, J.M. & Jolivet, L., 2003. Why did Arabia separate from Africa? Insights from 3-D laboratory experiments, *Earth planet. Sci. Lett.*, **216**, 365–381, doi:10.1016/S0012-821X(03)00516-8.
- Ben-Avraham, Z., Garfunkel, Z. & Lazar, M., 2008. Geology and evolution of the southern Dead Sea Fault with emphasis on subsurface structure, *Ann. Rev. Earth planet. Sci.*, **36**, 357–387.
- Bilham, R., 2006. Dangerous tectonics, fragile buildings, and tough decisions, *Science*, **311**, 1873–1875, doi:10.1126/science.1125176.
- Billen, M.I., 2008. Modeling the dynamics of subducting slabs, *Ann. Rev. Earth planet. Sci.*, **36**, 325–356, doi:10.1146/annurev.earth.36.031207.124129.
- Calais, E., DeMets, C. & Nocquet, J.-M., 2003. Evidence for a post-3.16 Ma change in Nubia-Eurasia-North America plate motions? *Earth planet. Sci. Lett.*, **216**, 81–92, doi:10.1016/S0012-821X(03)00482-5.
- Chaimov, T.A., Barazangi, M., Al-Saad, D., Sawaf, T. & Gebran, A., 1990. Crustal shortening in the Palmyride fold belt, Syria, and implications for movement along the Dead Sea fault, *Tectonics*, **9**, 1369–1386.
- Chu, D. & Gordon, G., 1998. Current plate motions across the Red Sea, *Geophys. J. Int.*, **135**, 313–328.
- Cloetingh, S., van der Beek, P.A., van Rees, D., Roep, Th.B., Biermann, C. & Stephenson R.A., 1992. Flexural interaction and the dynamics of Neogene extensional basin formation in the Alboran-Betic region, *Geo-Marine Lett.*, **12**, 66–75.
- Cochran, J.R., 1981. The Gulf of Aden: structure and evolution of a young ocean basin and continental margin, *J. geophys. Res.*, **86B**, 263–288.
- Cochran, J.R., 1983. A model for the development of the Red Sea, *AAPG Bull.*, **67**, 41–69.
- Conrad, C.P. & Lithgow-Bertelloni, C., 2002. How mantle slabs drive plate tectonics, *Science*, **298**(5591), 207–209, doi:10.1126/science.1074161.
- DeMets, C., Gordon, R. & Royer, J.-Y., 2005. Motion between the Indian, Capricorn, and Somalia plates since 20 Ma: implications for the timing and magnitude of distributed lithospheric deformation in the equatorial Indian Ocean, *Geophys. J. Int.*, **161**, 445–468, doi:10.1111/j.1365-246X.2005.x.
- Dercourt, J. *et al.*, 1979. Geological evolution of the Tethys Belt from the Atlantic to the Pamirs since the Lias, *Tectonophysics*, **123**, 241–315.
- Dewey, J.F., Helman, M.L., Turco, E., Hutton, D.H.W. & Knott, S.D., 1989. Kinematics of the western Mediterranean, *Geol. Soc. Lond. Spec. Pub.*, **45**, 265–283.
- Elsasser, W.M., 1971. Sea-floor spreading as thermal convection, *J. geophys. Res.*, **76**(5), 1101–1112.
- Forsyth, D.W. & Uyeda, S., 1975. On the relative importance of the driving forces of plate motion, *Geophys. J. R. astr. Soc.*, **43**, 163–200.
- Fournier, M., Camot-Rooke, N., Petit, C., Fabri, O., Huchon, P., Mailhot, B. & Lepvrier, C., 2008. *In situ* evidence for dextral active motion at the Arabia-India plate boundary, *Nature Geosci.*, **1**, 54–58, doi:10.1038/ngeo.2007.24.
- Garfunkel, Z. & Beyth, M., 2006. Constraints on the structural development of the Afar imposed by the kinematics of the major surrounding plates, *Geol. Soc. Lond. Spec. Pub.*, **259**, 23–42, doi:10.1144/GSL.SP.2006.259.01.04.
- Gautier, P., Brun, J.-P., Moriceau, R., Sokoutis, D. & Martinod, J.L., 1999. Timing, kinematics and causes of Aegean extension: a scenario based on a comparison with simple analog experiments, *Tectonophysics*, **315**, 31–72.
- Gomez, F., Khawlie, M., Tabet, C., Darkal, A.N., Khair, K. & Barazangi, M., 2006. Late Cenozoic uplift along the northern Dead Sea transform in Lebanon and Syria, *Earth planet. Sci. Lett.*, **241**, 913–931.
- Govers, R. & Wortel, M.J.R., 2005. Lithosphere tearing at STEP faults: response to edges of subduction zones, *Earth planet. Sci. Lett.*, **236**, 505–523, doi:10.1016/j.epsl.2005.03.022.
- Hager, B.H. & O'Connell, R.J., 1981. A simple global model of plate dynamics and mantle convection, *J. geophys. Res.*, **86**(B6), 4843–4867.
- Hager, B.H., King, R.W. & Murray, M.H., 1991. Measurements of crustal deformation using the global positioning system, *Ann. Rev. Earth planet. Sci.*, **19**, 351–382.
- Hempton, M.R., 1987. Constraints on Arabia plate motion and extensional history of the Red Sea, *Tectonics*, **6**, 687–705.
- Herring, T.A., King, R.W. & McClusky, S.C., 2010. *Introduction to GAMIT/GLOBK, Release 10.4*, MIT, Cambridge, MA, 48pp.
- Jackson, J., 1994. Active tectonics of the Aegean region, *Ann. Rev. Earth planet. Sci.*, **22**, 23–71.
- Joffe, S. & Garfunkel, Z., 1987. Plate kinematics of the circum Red Sea: a re-evaluation, *Tectonophysics*, **141**, 5–12.
- Jolivet, L. & Faccenna, C., 2000. Mediterranean extension and the Africa-Eurasia Collision, *Tectonics*, **19**, 1095–1106.
- Klinger, Y., Avouac, J.P., Abou Karaki, N., Dorbath, L., Bourles, D. & Reyss, J.L., 2000. Slip rate on the Dead Sea transform fault in the northern Araba valley (Jordan), *Geophys. J. Int.*, **142**, 755–768.
- Krijgsman, W. & Garces, M., 2004. Paleomagnetic constraints on the geodynamic evolution of the Gibraltar Arc, *Terra Nova*, **16**(5), 281–287, doi:10.1111/j.1365-3121.2004.00564.x.
- Le Pichon, X. & Angelier, J., 1979. The Hellenic arc and trench system: a key to the neotectonic evolution of the Mediterranean area, *Tectonophysics*, **60**, 1–42.
- Le Pichon, X. & Gaulier, J.M., 1988. The rotation of Arabia and the Levant fault system, *Tectonophysics*, **153**, 271–294.
- Le Pichon, X. & Kreemer, C., 2010. The Miocene to present kinematic evolution of the Eastern Mediterranean and Middle East and its implications for dynamics, *Ann. Rev. Earth planet. Sci.*, **38**, 323–351, doi:10.1146/annurev-earth-040809-152419.
- McClusky, S. *et al.*, 2000. GPS constraints on plate kinematics and dynamics in the eastern Mediterranean and Caucasus, *J. geophys. Res.*, **105**, 5695–5719, doi:10.1029/1999JB900351.
- McClusky, S., Reilinger, R., Mahmoud, S., Ben Sari, D. & Tealeb, A., 2003. GPS constraints on Africa (Nubia) and Arabia plate motion, *Geophys. J. Int.*, **155**, 126–138.
- McClusky, S. *et al.*, 2010. Kinematics of the southern Red Sea–Afar Triple Junction and implications for plate dynamics, *Geophys. Res. Lett.*, **37**, doi:10.1029/2009GL041127.
- McKenzie, D.P., 1970. Plate tectonics of the Mediterranean region, *Nature*, **226**, 239–243.
- McKenzie, D.P., Davies, D. & Molnar, P., 1970. Plate tectonics of the Red Sea and East Africa, *Nature*, **226**, 243–248.
- McQuarrie, N., Stock, J.M., Verdel, C. & Wernicke, B.P., 2003. Cenozoic evolution of Neotethys and implications for the causes of plate motions, *Geophys. Res. Lett.*, **30**, doi:10.1029/2003GL017992.
- Molnar, P. & Stock, J.M., 2009. Slowing of India's convergence with Eurasia since 20 Ma and its implications for Tibetan mantle dynamics, *Tectonics*, **28**, doi:10.1029/2008TC002271.
- Niemi, T.M., Zhang, H., Atallah, M. & Harrison, J.B.J., 2001. Late Pleistocene and Holocene slip rate of the Northern Wadi Araba fault, Dead Sea Transform, Jordan, *J. Seismol.*, **5**, 449–474.
- Platt, J.P. & Vissers, R.L.M., 1989. Extensional collapse of thickened continental lithosphere: a working hypothesis for the Alboran Sea and Gibraltar Arc, *Geology*, **17**, 540–543, doi:10.1130/0091-7613.
- Reilinger, R. *et al.*, 2006. GPS constraints on continental deformation in the Africa–Arabia–Eurasia continental collision zone and implications for the dynamics of plate interactions, *J. geophys. Res.*, **111**, B05411, doi:10.1029/2005JB004051.
- Royden, L., 1993. The tectonic expression of slab pull at continental convergent boundaries, *Tectonics*, **12**, 303–325.
- Royden, L. & Husson, L., 2009. Subduction with variations in slab buoyancy: models and application to the Banda and Apennine systems, in *Subduction Zone Geodynamics*, Frontiers in Earth Sciences, eds Funicello, F. & Lallemand, S., Springer, Berlin, doi:10.1007/978-3-540-87974-9.



- Turcotte, D.L. & Schubert, G., 2002. *Geodynamics*, 2nd edn, Cambridge University Press, Cambridge, UK.
- Wortel, M.J.R. & Spakman, W., 2000. Subduction and slab detachment in the Mediterranean-Carpathian region, *Science*, **290**(5498), doi:10.1126/science.290.5498.1910.

## SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

**Table S1.** GPS horizontal velocities with respect to Eurasia (given in terms of east [E] and north [N] rate) and 1-sigma uncertainties ( $\pm$ ). GPS sites (indicated by 4-character ID) used to constrain plate motions are identified with a specific plate (AF = Africa, AR = Arabia, AU = Australia, EU = Eurasia, IN = India). Abbreviations: Lon = longitude, Lat = latitude, RHO = correlation between N and E velocity components.

**Table S2(a).** Euler vectors and associated 1-sigma uncertainties ( $\pm$ ) for the Nubian (NU), Arabian (AR), Anatolian (AN), Indian (IN) and Australian (AUS) plates with respect to Eurasia (EU). Abbreviations: lat = latitude, long = longitude, lat/lon = correlation between lat and long, lat/rate = correlation between lat and rate, lon/rate = correlation between lon and rate.

**Table S2(b).** Cartesian Euler Vectors and associated 1-sigma uncertainties ( $\pm$ ) for the Nubian (NU), Arabian (AR), Anatolian (AN), Indian (IN) and Australian (AUS) plates with respect to Eurasia (EU). Abbreviations:  $\omega_x, \omega_y, \omega_z$  = Euler rotation rates around the X, Y, Z Cartesian axes in degrees per million years ( $\text{deg Myr}^{-1}$ ). X/Y, X/Z, Y/Z are the correlations between the X, Y and Z rotation estimates.

Please note: Wiley-Blackwell is not responsible for the content or functionality of any supporting materials supplied by the authors. Any queries (other than missing material) should be directed to the corresponding author for the article.